Vision

By the year 2025, effective, safe, and cost-competitive options for geologic sequestration of all of the CO_2 generated from coal, oil, and gas power plants and generated by H_2 production from fossil fuels will be available within 500 km of each power plant.

5 SEQUESTRATION OF CARBON DIOXIDE IN GEOLOGIC FORMATIONS

5.1 SEQUESTRATION IN GEOLOGIC FORMATIONS BUILDS ON A STRONG EXPERIENCE BASE

Geologic formations, such as oil fields, coal beds, and aquifers, are likely to provide the first large-scale opportunity for concentrated sequestration of CO_2. In fact, CO_2 sequestration is already taking place at Sleipner West off the coast of Norway, where approximately one million tonnes of CO_2 are sequestered annually as part of an off-shore natural gas production project (see sidebar on the Statoil Project). Developers of technologies for sequestration of CO_2 in geologic formations can draw from related experience gained over nearly a century of oil and gas production, groundwater resource management, and, more recently, natural gas storage and groundwater remediation. In some cases, sequestration may even be accompanied by economic benefits such as enhanced oil recovery (EOR), enhanced methane production from coal beds, enhanced production of natural gas from depleted fields, and improved natural gas storage efficiency through the use of CO_2 as a “cushion gas” to displace methane from the reservoir.

5.1.1 Sequestration Mechanisms

CO_2 can be sequestered in geologic formations by three principal mechanisms (Hitchon 1996; DOE 1993). First, CO_2 can be trapped as a gas or supercritical fluid under a low-permeability caprock, similar to the way that natural gas is trapped in gas reservoirs or stored in aquifers. This mechanism, commonly called hydrodynamic trapping, will likely be, in the short term, the most important for sequestration. Finding better methods to increase the fraction of pore space

Statoil Sequesters CO_2 from Off-Shore Gas Production

Natural gas produced from the Sleipner West field in the North Sea contains nearly 10% by volume CO_2. To meet the sales specification of only 2.5% CO_2, most of the CO_2 must be removed from the natural gas before delivery. Statoil uses an amine solvent to absorb the excess CO_2. The separated CO_2 is injected into an aquifer 1000 m under the North Sea. Approximately one million tonnes of CO_2 are separated and sequestered annually. Over the project lifetime, 20 million tonnes of CO_2 are expected to be sequestered (Korbol and Kaddour 1995).

occupied by trapped gas will enable maximum use of the sequestration capacity of a geologic formation. Second, CO_2 can dissolve into the fluid phase. This mechanism of dissolving the gas in a liquid such as petroleum is called solubility trapping. In oil reservoirs, dissolved CO_2 lowers the viscosity of the residual oil so it swells and flows more readily, providing the basis for one of the more common EOR techniques. The relative importance of solubility trapping depends on a large number of factors, such as the sweep efficiency (efficiency of displacement of oil or water) of CO_2 injection, the formation of fingers (preferred flow paths), and the effects of formation heterogeneity. Efficient solubility trapping will reduce the likelihood that CO_2 gas will quickly return to the atmosphere.

Finally, CO_2 can react either directly or indirectly with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. In most geologic formations, formation of calcium, magnesium, and iron carbonates is expected to be the primary mineral-trapping processes. However, precipitation of these stable mineral phases is a relatively slow process with poorly understood kinetics. In coal formations, trapping is achieved by preferential adsorption of CO_2 to the solid matrix. Developing methods for increasing the rate and capacity for mineral trapping will create stable repositories of carbon that are unlikely to return to the biosphere and will decrease unexpected leakage of CO_2 to the surface.

Finding ways to optimize hydrodynamic trapping, while increasing the rate at which the other trapping mechanisms convert CO_2 to less mobile and stable forms, is one of the major challenges that must be addressed by an R&D program.

5.1.2 Sources and Forms of CO_2

For the purposes of this assessment, we assumed that CO_2 would be produced either by combustion of fossil fuels to generate electricity or by decarbonization of fossil fuels to produce hydrogen. Following generation, CO_2 would be separated from the waste stream to a purity of at least 90%. CO_2 would be transported as a supercritical fluid by pipeline to the nearest geologic formation suitable for sequestration. The technology, cost, and safety issues for transportation were not considered, but it is likely that the costs will be significant and must be included for any valid comparison among projects and ideas.

5.1.3 Capacity of Geologic Formations Suitable for Sequestration

Three principal types of geologic formations are widespread and have the potential to sequester large amounts of CO_2:

- active and depleted oil and gas reservoirs
- deep brine formations, including saline formations
- deep coal seams and coal-bed methane formations

Other geologic formations such as marine and arctic hydrates, CO_2 reservoirs, mined cavities in salt domes, and oil shales may increase sequestration capacity or provide site-specific opportunities but are likely to be developed only after other sequestration targets are explored.

Maps showing the location of active and abandoned oil and gas fields, deep-saline aquifers, and coal formations are provided in Figs. 5.1 through 5.3. Figure 5.3 also shows the location of fossil-fuel-fired power plants. As illustrated, one or more of these formations is located within 500 km of each of the fossil-fuel-burning power plants in the United States.

Estimates of sequestration capacity for each of these types of geologic formations are provided in Table 5.1. While the range and uncertainty in these estimates are large, and in some cases costs were not considered when they were developed, they suggest that a significant opportunity exists for CO_2 sequestration in geologic formations. More specifically, in the near term, the United States has sufficient capacity, diversity, and broad geographic distribution of geological formations to pursue geologic sequestration confidently as a major component of a national carbon management strategy. What is less certain is the ultimate capacity that geologic formations can contribute, over the centuries ahead, to sequestration of CO_2. Only through experience and application of systematic screening criteria will we gain enough knowledge to assess the ultimate sequestration capacity of geologic formations.

5.1.4 Drivers for R&D

Although the potential for CO_2 sequestration in geologic formations is promising, new knowledge, enhanced technology, and operational experience must be gained in a number of critical areas. The primary drivers for R&D include

- developing reliable and cost-effective systems for monitoring CO_2 migration in the subsurface
- assessing and ensuring long-term stability of sequestered CO_2 (>100 years)

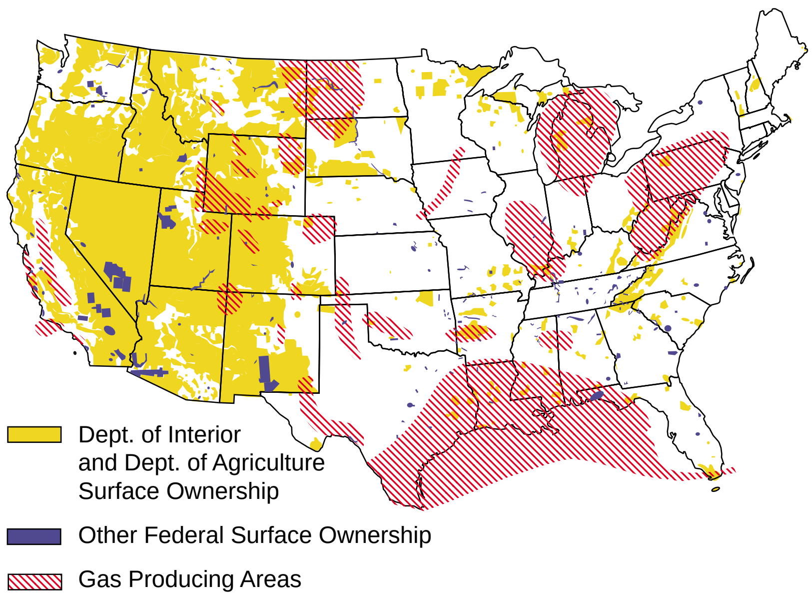


Fig. 5.1. Location of gas-producing areas in the United States.

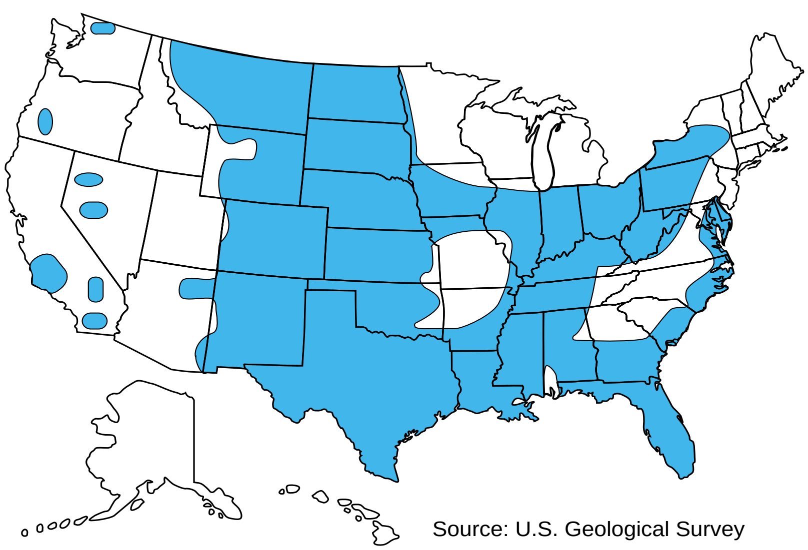


Fig. 5.2. Location of deep saline aquifers in the United States.

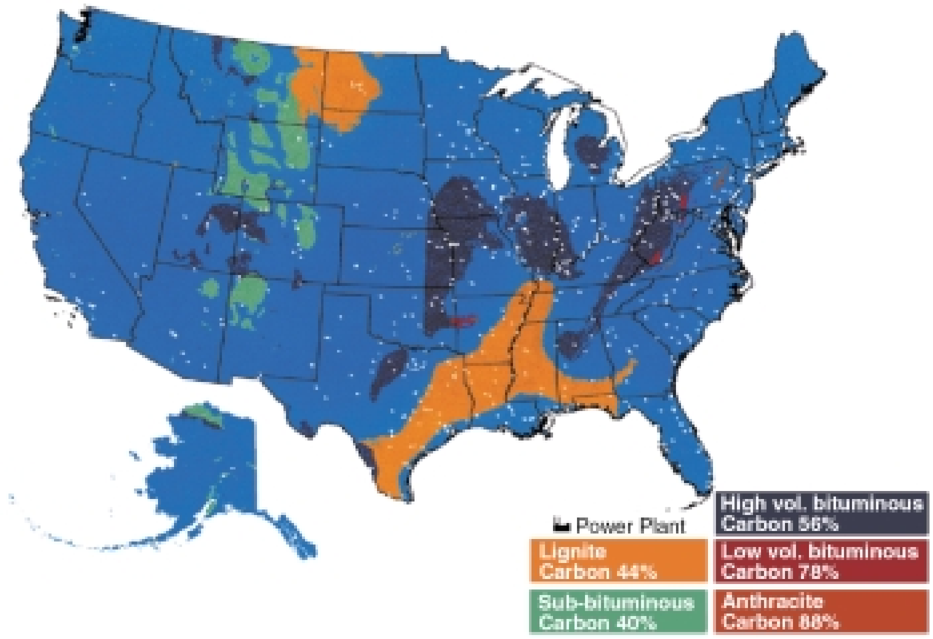


Fig. 5.3. Location of coal-producing areas in the United States and power plants.

Table 5.1. Range of estimates for CO_2 sequestration in U.S. geologic formations

Geologic formation	Capacity estimate (GtC)	Source
Deep saline aquifers	1-130	Bergman and Winter 1995
Natural gas reservoirs in the United States	25[a] 10[b]	R. C. Burruss 1977
Active gas fields in the United States	0.3/year[c]	Baes et al. 1980
Enhanced coal-bed methane production in the United States	10	Stevens, Kuuskraa, and Spector 1998

[a]Assuming all gas capacity in the United States is used for sequestration.
[b]Assuming cumulative production of natural gas is replaced by CO_2.
[c]Assuming that produced natural gas is replaced by CO_2 at the original reservoir pressure.

- reducing the cost and energy requirements of CO_2 sequestration in geologic formations
- gaining public acceptance for geologic sequestration

This chapter outlines R&D needs to address these issues and provides a comprehensive road map of the critical elements needed to achieve the potential of geologic sequestration of CO_2.

5.2 ASSESSMENT OF CURRENT CAPABILITIES AND R&D NEEDS

The current capabilities and needs were evaluated in the following context for each major type of geologic formation.

Industrial experience: What related industrial experience provides the scientific, technological, and economic basis for evaluating sequestration in geologic formations?

Beneficial uses of CO_2: Are there beneficial uses of CO_2 that may offset the cost of sequestration or provide an additional incentive for developing CO_2 sequestration technology?

Regulatory, cost, and safety: What is known about the regulatory framework, cost, and safety aspects of CO_2 sequestration in geologic formations?

Operational drivers: What are the operational aspects that must be understood to enable cost-effective and safe sequestration of CO_2? These include

- *CO_2 trapping mechanisms:* Which of the trapping mechanisms is most important? How much do we understand about them? What are the key unresolved issues?
- *Multiphase flow:* pathways in porous media, including reaction path modeling.
- *CO_2 waste stream characteristics:* What are the requirements for the CO_2 waste stream? How pure should it be? What are the effects of impurities on sequestration efficiency, cost, safety, and risk? What temperature and pressure are needed at the wellhead? What are the unresolved issues?
- *Formation characterization:* How can sequestration capacity and caprock integrity be assessed? What attributes are most important for assessing capacity and integrity?
- *Injection, drilling, and well completion technology:* How will CO_2 be injected into geologic formations? How will the wells be drilled and completed? Are there special material-handing issues for sequestration of CO_2?
- *Performance assessment:* What methods can be used to design, predict, and optimize sequestration of CO_2 in geologic formations? What new issues must to be addressed or new approaches will be required?
- *Monitoring:* How can migration of CO_2 in the subsurface be monitored? How can leakage be detected and quantified? How can we detect and monitor solubility and mineral trapping?

In the following sections, we first address these questions in the context of issues unique to each type of geologic formation. Next we address cross-cutting issues that are common to all formations.

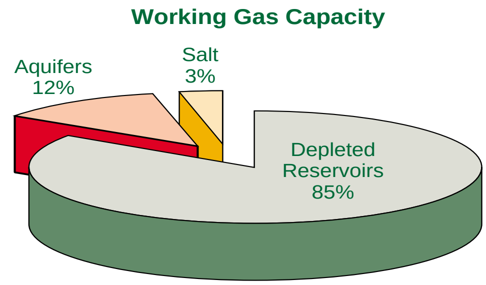
5.2.1 Opportunities for CO_2 Sequestration in Oil and Gas Formations

Oil and gas reservoirs are promising targets for CO_2 sequestration for a number of reasons. First, oil and gas are present within structural or stratigraphic traps, and the oil and gas that originally accumulated in these traps did not escape over geological time. Thus these reservoirs should also contain CO_2, as long as pathways to the surface or to adjacent formations are not created by overpressuring of the reservoir, by fracturing out of the reservoir at wells, or by leaks around wells. Second, the geologic structure and physical properties of most oil and gas fields have been characterized extensively. While additional characterization—particularly of the integrity and extent of the caprock—may be needed, the availability of existing data will lower the cost of implementing CO_2 sequestration projects. Finally, very sophisticated computer models have been developed in the oil and gas industry to predict displacement behavior and trapping of

CO_2 for EOR. These models take into account the flow of oil, gas, and brine in three dimensions; phase behavior and CO_2 solubility in oil and brine; and the spatial variation of reservoir properties, to the extent it is known. These same processes are responsible for hydrodynamic and solubility trapping of CO_2 (see sidebar on natural gas storage).

The first and most viable option for CO_2 sequestration is to build upon the enormous experience of the oil and gas industry in EOR. Currently, about 80% of commercially used CO_2 is for EOR purposes. The technology for CO_2 injection is commercially proven and can be implemented without much difficulty (see sidebar on auxiliary benefits of CO_2 sequestration). EOR has the benefit of sequestering CO_2 while increasing production from active oil fields. In the long term, the volume of CO_2 sequestered as part of EOR projects may not be comparatively large, but valuable operational experience can be gained that will benefit geologic sequestration in other types of formations.

Natural Gas Storage in Geologic Formations



Daily and seasonal variability in demand for natural gas requires the storage of large volumes of natural gas that can be tapped as needed. Geologic formations are used to store natural gas. Currently, they provide 3 trillion ft^3 of working gas capacity. Most gas is stored in depleted gas fields, but aquifers and mined caverns in salt also contribute significantly to the existing capacity. Natural gas storage provides experience in and demonstrates the feasibility of the hydrodynamic trapping mechanism for use in sequestering CO_2 (Beckman and Determeyer 1995).

CO_2 could be sequestered in two types of natural gas fields: (1) abandoned fields and (2) depleted but still active fields where gas recovery could be enhanced by CO_2 injection. The map in Fig. 5.1 suggests that, except for the North Central and Atlantic Coastal states, abandoned gas fields are present in many parts of the United States. Deciding which abandoned gas fields could best be used in a CO_2 sequestration program would require a comprehensive review of the current conditions in abandoned fields and the economics of their rehabilitation. This would be a major program of investigation, but the necessary technology to carry out such a review is available and well known to the gas industry. Locating and sealing abandoned wells may be an ongoing challenge for sequestration in abandoned gas fields.

In nearly depleted gas fields, it is possible that injection could prolong the economic life of the field by maintaining reservoir pressures longer than would otherwise be possible. However, enhancing gas production through injection of another kind of gas (e.g., CO_2) while the field continues to operate has not been pursued in the United States. Therefore, pilot tests augmented with laboratory and modeling studies will be needed to develop this technology. Some

CO_2 Sequestration in Geological Formations Can Have Auxiliary Benefits

Recovering residual oil through the injection of CO_2 into oil reservoirs began on a large scale in 1972 in Texas. Carbon dioxide enhances oil production by two primary mechanisms. First, CO_2 gas displaces oil and brine, which are subsequently pumped from the wells. Second, injected CO_2 dissolves in the oil, leading to a reduction in viscosity and swelling of the oil, making it flow more easily and leading to enhanced production. The CO_2 used for EOR usually comes from naturally occurring CO_2-filled reservoirs. Pipelines carry CO_2 from its natural reservoirs to the oil field, where it is injected. Eventually, some of the injected CO_2 is produced along with the oil. At the surface, it is separated and injected back into the oil reservoir. EOR through CO_2 injection provides one example of the beneficial uses of CO_2 and operational experience to guide CO_2 sequestration.

In the future, CO_2 sequestered from power plants can be used to enhance coal-bed methane production. A pilot program of CO_2-assisted coal-bed methane production in the San Juan Basin, New Mexico, has been under way since 1996. This project, the Allison Unit Pilot run by Burlington Resources, is injecting 4 million ft^3/day of pipeline-fed CO_2 from a natural source into a system of nine injection wells located in the San Juan Basin. Preliminary results indicate that full-field development of this process could boost recovery of in-place methane by about 75%.

experience may be gained from Gaz de France, which for the past 10 to 15 years has been converting gas storage projects to operate with two kinds of gas: natural gas that is cyclically injected and withdrawn as needed and a low-cost cushion gas. A similar concept may be developed for combining CO_2 sequestration with enhanced natural gas production from depleted fields.

Table 5.2 lists the specific R&D needs for advancing the technology and acceptability of CO_2 sequestration in oil and gas reservoirs. Needs are divided into near-, mid-, and long-term efforts that together provide a comprehensive set of actions that will create a set of sequestration options.

5.2.2 CO_2 Sequestration in Brine Formations

Brine formations are the most common fluid reservoirs in the subsurface, and large-volume formations are available practically anywhere. For sequestration, deep (>2000 ft) formations that are not in current use are the most logical targets. As shown in Fig. 5.2, suitable deep formations, which are usually filled with brackish or saline water, are located across most of the United States. Brine formations have the largest potential capacity and are the most challenging of the potential sequestration options.

Although there is little practical experience with CO_2 sequestration in brine formations, aquifer storage of natural gas provides a foundation of experience for identifying important technical issues. In addition, CO_2 sequestration in aquifers has been discussed in the technical literature since the early 1990s. Operational experience from aquifer gas storage and these studies indicate that from an engineering perspective, the main issues for CO_2 disposal in aquifers

Table 5.2. R&D priorities for CO_2 sequestration in oil and gas fields

Near-term R&D (<2005)	Mid-term R&D (2005-2010)	Long-term R&D (>2010)
Understand the importance of geochemical reactions on - seal integrity - long-term sequestration - subsidence - long-term oil recovery	Complete assessment of monitoring methods for monitoring CO_2 - Enhance resolution of seismic monitoring method - Develop verification and monitoring capabilities for CO_2 sequestration in EOR applications - Evaluate and develop electrical methods for CO_2 monitoring - Evaluate and develop methods for monitoring solubility and mineral mapping	Obtain cost and performance data from a full-scale integrated demonstration of CO_2 sequestration from a power plant in a depleted or abandoned gas field
Develop coupled H-M-C-T (hydrologic, mechanical, chemical, thermal) simulators for evaluating short- and long-term sequestration efficiency and safety	Conduct a small-scale pilot for improved gas recovery from a depleted gas field by CO_2 injection	Develop methods to increase sequestration efficiency from current estimates (1-10% pore volume) to greater than 50%
Establish screening criteria for selecting sequestration sites in oil and gas fields - Highest priority should be given to EOR projects - Next highest priority to abandoned gas fields - Match CO_2 generators to potential sequestration sites	Implement pilot test for co-optimization of CO_2 EOR and sequestration	
Assess and develop methods for detection of abandoned wells in oil and gas fields		

relate to (1) the disposal rate of CO_2; (2) the available storage capacity (ultimate CO_2 inventory); (3) the presence of a caprock of low permeability, and potential CO_2 leakage through imperfect confinement; (4) identification and characterization of suitable aquifer formations and caprock structures; (5) uncertainty due to incomplete knowledge of subsurface conditions and processes; and (6) corrosion resistance of materials to be used in injection wells and associated facilities.

The main trapping process affecting CO_2 sequestration in aquifers is well understood, at least in a generic sense. Injection of CO_2 into a water-filled formation results in immiscible displacement of an brine phase by a less dense and less viscous gas phase. Because CO_2 is soluble in water, some of the CO_2 will dissolve in the water. The thermophysical properties of water and CO_2 that determine flow behavior—such as density, viscosity, and solubility—are well known, as is their dependence on pressure, temperature, and salinity. Equilibrium solubility of CO_2 in water decreases by about a factor of 6 between 10 and 150°C, and it decreases with aquifer salinity ("salting out"). The rate at which gaseous CO_2 will dissolve in water depends on size and shape of the gas-water interfaces and may be subject to considerable uncertainty.

Uptake of CO_2 by water may be increased beyond what can be attributed to physical solubility by interactions with carbonate minerals. Minerals such as calcite would be dissolved in response to CO_2 injection. A considerably larger increase in storage capacity is possible from heterogeneous reactions with aluminosilicates ("mineral trapping"). There are indications that kinetics of reactions with carbonates may be fast, while kinetics of silicate interactions appear to be very slow, requiring tens or perhaps hundreds of years for substantial reaction progress.

Because CO_2 is considerably less dense and viscous than water, CO_2 injection into aquifers will be prone to hydrodynamic instabilities. The viscosity contrasts will lead to viscous fingering, and the density contrast will lead to gravity segregation. The specifics of each will depend on the spatial distribution of permeability at the actual site and on injection rates (Fig. 5.4). The effect of these complexities may be important in controlling the relative importance of the three primary trapping mechanisms. Detailed characterization of these complexities will be difficult, but it may not be necessary for achieving engineering objectives.

Two key issues distinguish CO_2 sequestration in aquifers from

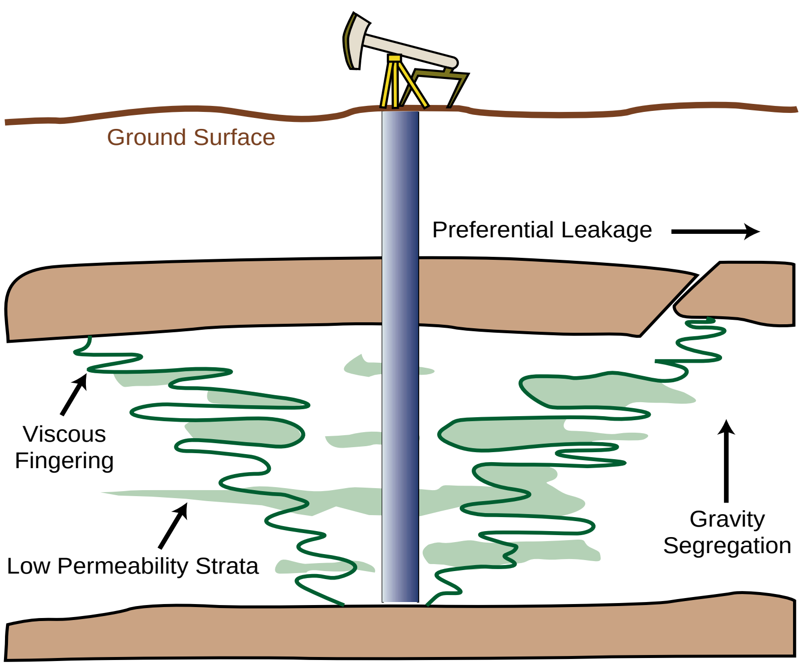


Fig. 5.4. Gravity segregation, viscous fingering, heterogeneity, and preferential flow through faulted cap rocks could influence CO_2 migration in the subsurface.

sequestration in oil and gas reservoirs. First, oil and gas reservoirs occur by virtue of the presence of a structural or stratigraphic trap. This same trap is likely to retain CO_2. Identification of such effective traps may be more difficult in brine formations and may require new approaches for establishing the integrity and extent of a caprock. Second, injection of CO_2 into an brine formation is unlikely to be accompanied by removal of water from the formation. (In the case of EOR, oil is simultaneously withdrawn while CO_2 is injected.) Injection will therefore lead to an increase in formation pressure over a large area. Whether or to what extent large-scale pressurization will affect caprock integrity, cause land surface deformation, and induce seismicity must be better understood to design safe and effective sequestration.

A final issue concerning sequestration in brine formations is the accep-table leakage rate from the formation to overlying strata. Leakage of CO_2 may not pose a safety hazard and may, in some cases, be desirable if leakage to overlying units increases the opportunity for enhanced solubility or mineral trapping. Evaluating general and site-specific acceptable leakage rates should be part of a long-term strategy for CO_2 sequestration in brine formations.

Table 5.3 lists the specific R&D needs for advancing the technology and acceptability of CO_2 sequestration in brine formations. Needs are divided into near-, mid-, and long-term efforts that together provide a comprehensive set of actions that will create a set of sequestration options.

5.2.3 Opportunities for CO_2 Sequestration in Coal Formations

Coal formations provide an opportunity to simultaneously sequester CO_2 and increase the production of natural gas. Methane production from deep unmineable coal beds can be enhanced by injecting CO_2 into coal formations, where the adsorption of CO_2 causes the desorption of methane. This process has the potential to sequester large volumes of CO_2 while improving the efficiency and profitability of commercial natural gas operations (see sidebar on auxiliary benefits of CO_2 sequestration).

This method for enhancing coal-bed methane production is currently being tested at two pilot demonstration sites in North America. At one pilot production field in the San Juan Basin (New Mexico and Colorado), the operator has injected 3 million ft^3/day of CO_2 through four injection wells during a 3-year period. Preliminary results indicate that full-field development of this process could boost recovery of in-place methane by about 75%. The key technical and commercial criteria for successful application of this concept include (1) favorable geology such as thick, gas-saturated coal seams, buried at suitable depths and located in simple structural settings, which have sufficient permeability; (2) CO_2 availability, such as low-cost potential supplies of CO_2, either from naturally occurring reservoirs or from anthropogenic sources such as power-plant flue gas; and (3) gas demand, which includes an efficient market for utilization of methane, including adequate pipeline infrastructure, long-term end-users, and favorable wellhead gas prices.

Table 5.3. R&D priorities for CO_2 sequestration in brine formations

Near-term R&D (<2005)	Mid-term R&D (2005-2010)	Long-term R&D (>2010)
Develop a small-scale pilot test of CO_2 into a shallow <3000-ft-deep aquifer or facility for brine formation	Understand the kinetics of CO_2 dissolution and mineral trapping	Obtain cost and performance data from a full-scale integrated demonstration of CO_2 sequestration from a power plant in moderate depth (2000-5000 ft) saline formation
Develop coupled H-M-C-T (hydrologic, mechanical, chemical, thermal) simulators for evaluating short and long-term sequestration efficiency and safety	Understand how pressure buildup due to CO_2 injection influences caprock integrity	Develop technologies to mitigate or control CO_2 leaks
Establish screening criteria for selecting sequestration sites in aqueous formations. Match CO_2 generators to potential sequestration sites using screening criteria	Understand reservoir characteristics to minimize adverse effects on caprock integrity during CO_2 injection	Develop advanced concepts and technologies for improving sequestration efficiency
Evaluate and develop, if needed, methods for evaluating the integrity of caprocks. Develop a safety analysis and technical strategy for the concept of an "allowable" leakage rate	Use natural CO_2 reservoirs to understand how long-term mineral trapping may contribute to permanent sequestration	Develop remote or other cost-effective methods for monitoring CO_2 leaks
Develop methods for monitoring migration of CO_2 and its byproducts in the subsurface using a combination of hydrologic, seismic, tracer, and mechanical methods (e.g., tilt measurements)	Evaluate the potential for induced seismicity associated with CO_2 injection	

A second pilot demonstration of this concept is located in Alberta, Canada. The Alberta project is testing a process of injecting CO_2 into one of Alberta's deep unmineable coal beds. Many of Alberta's coal deposits are rich in methane. Preliminary computer modeling suggests that selected techniques for fracturing the coals around wells could be improved with a substantial increase in primary methane. The initial field activities consist of a single well test, designed to measure reservoir properties, increase primary production by an effective fracturing technique, and evaluate CO_2-enhanced methane recovery. A detailed technical assessment will follow the field test in early 1999.

Coal-bearing strata include both thin and thick coal seams and interlayered sandstones, siltstones, and shales; and they are usually saturated with water. This complex interlayered formation defines the coal-bed reservoir interval. Coal-bed stratigraphy and the structure/porosity/permeability of interlayered and overlying strata are site-specific and will need to be individually characterized. Unlike in oil and gas reservoirs, however, the methane in coal beds is retained by adsorption rather than by trapping beneath an impermeable overlying/

lateral seal. Therefore, the nature of overlying and adjacent strata becomes an important issue for retention of the CO_2 within the coal-bed reservoir interval until it is adsorbed, and for retention of the displaced methane until it can be withdrawn. Techniques to verify the capacity, stability, and permanence of CO_2 storage in coal-bed reservoir intervals are needed.

Table 5.4 lists the specific R&D needs for advancing the technology and acceptability of CO_2 sequestration in coal formations. Needs are divided into near-, mid-, and long-term efforts that together provide a comprehensive set of actions that will create a set of sequestration options.

5.3 CROSS-CUTTING R&D NEEDS FOR GEOLOGIC FORMATIONS

Operational requirements and R&D needs for sequestration in each of the three types of geologic formations were assessed independently. Not unexpectedly, needs common to all formations emerged and are summarized in this section. There are significant differences, however, in the maturity of technology and scientific understanding of the processes underpinning CO_2 sequestration in different types of geologic formations. Figure 5.5 highlights these similarities and differences.

A critical cross-cutting R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues, but also has as a principal goal gaining public confidence in geologic sequestration. Without public confidence, progress on technical issues will be of limited impact. Moreover, regulatory oversight bodies, CO_2 generators, and sequestration site operators will need to come to agreement about protocols for assessment, evaluation, and monitoring. A strong scientific foundation is critical to the success of the geologic sequestration option.

5.3.1 CO_2 Trapping Mechanisms

Hydrodynamic and solubility processes responsible for trapping CO_2 in geologic formations are reasonably well understood, especially over the time frame associated with EOR (<20 years). Mineral trapping (i.e., reactions relying on the chemical reactions between the gas/liquid and solid phases) is less well understood, particularly with regard to how fast these reactions occur. Reactions between CO_2 and the microbial communities present in deep geologic formations are also poorly understood. Needs for new knowledge include

- hydrodynamics of CO_2 migration in heterogeneous formations (e.g., sweep efficiency, preferential flow, and leakage rates)
- CO_2 dissolution kinetics
- mineral trapping kinetics
- microbial interactions with CO_2
- influence of stress changes on caprock and formation integrity
- nonlinear feedback processes affecting confinement (e.g., mineral dissolution and precipitation that change rock permeability)
- CO_2–methane adsorption/exchange behavior on organic substrates

5.3.2 CO_2 Waste Stream Characteristics

A high-purity (>90% CO_2), dry waste stream is the most desirable for sequestration in geological formations, based largely on considerations about volume reduction, costs for gas compression, and CO_2 handling issues (e.g., corrosion). Scoping studies are

Table 5.4. R&D priorities for CO_2 sequestration in coal formations

Near-term R&D (<2005)	Mid-term R&D (2005-2010)	Long-term R&D (>2010)
Physical and chemical properties of coal - Adsorption/desorption of CO_2 - Interaction with SOx and NOx - Absolute and relataive permeability - Swelling behavior from CO_2 absorption	Develop H-C-M-T modeling tools for simultaneous fluid flow, gas adsorption-desorption, deformation and gas-flow dynamics in coal-bed reservoir intervals	Obtain cost and performance data from a full-scale integrated demonstration of methane production, power generation, and CO_2 sequestration
Develop reservoir screening criteria for assessment purposes. Match CO_2 generators to potential sequestration sites using screening criteria	Conduct a pilot test of flue gas injection to evaluate ability of CO_2 to adsorb to the coal surface, displacing the methane, while the nitrogen sweeps the methane	Develop technologies and methods for injection and production in low-permeability and deep formations
	Develop injection engineering and design techniques for optimizing CO_2 sequestration and methane production in coal beds	Test CO_2, methane, coal interactions in water-saturated intervals to evaluate whether dewatering is needed prior to CO_2 injection
	Develop methods for monitoring migration of CO_2 and its byproducts using a combination of hydrologic, seismic, tracer, and mechanical methods	Evaluate the impact of microbial activity on the long-term fate of CO_2 in coal formations

needed to evaluate beneficial or detrimental effects of waste stream characteristics on trapping efficiency, economics, and safety of CO_2 sequestration. Examples of research needs include

- analysis of the effect of waste stream characteristics on hydrodynamic, solubility, and mineral trapping/adsorption efficiency
- cost/benefit analysis for determining optimal CO_2 purity
- evaluation of the influence of other “contaminants” (e.g., mercury) on the safety and regulatory constraints on CO_2 sequestration

5.3.3 Formation Characterization

Ongoing efforts related to oil and gas production and groundwater remediation have led to development of hydraulic, geophysical imaging, and geostatistical techniques for characterizing the heterogeneity of sedimentary and fractured geological formations. These will be needed to predict the sweep efficiency in brine formations. Additional needs specific to sequestration include

- caprock characterization
- identification of leakage paths and rates
- evaluation of hydrologic isolation through the use of isotopic and other chemical analyses

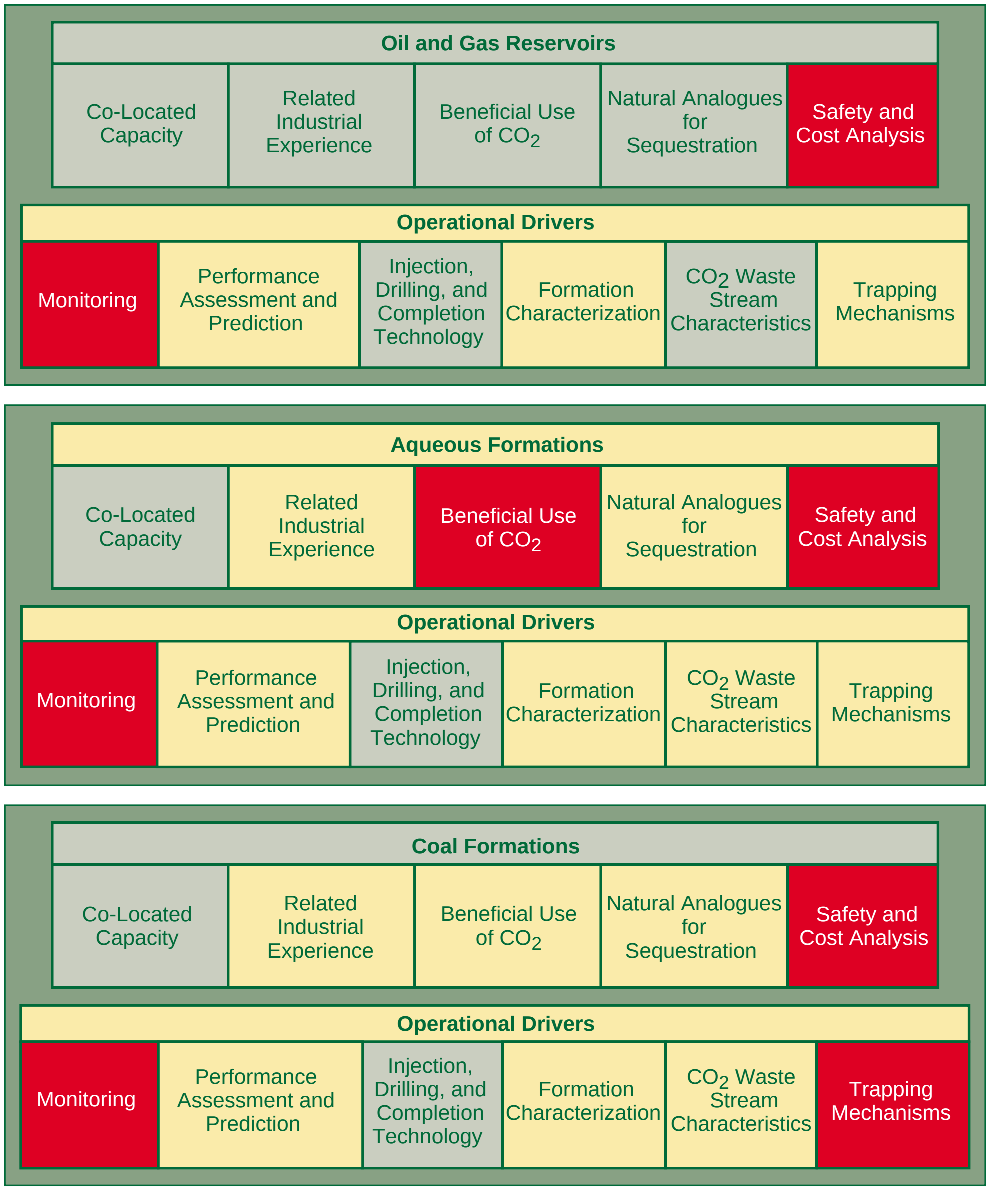


Fig. 5.5. Comparative evaluation of the technological and scientific maturity of operational requirements for sequestering CO_2 in geologic formations. Gray signifies that the technology and scientific understanding are mature and ready to go. White indicates that some experience base is available but more experience is needed to evaluate and improve sequestration options. Black signifies that key processes, parameters, technologies, and an understanding of fundamental processes must improve significantly to achieve our vision for geological sequestration.

- identification of mineral assemblages that influence mineral trapping and caprock integrity
- water encroachment in dewatered formations
- reservoir compartmentalization
- initial conditions and evolution of joints and fracture networks from stress and chemically induced deformation

5.3.4 Injection, Drilling, and Well Completion Technology

Injection, drilling, and completion technology for the oil and gas industry has evolved to a highly sophisticated state so that it is possible to drill and complete vertical, slanted, and horizontal wells in deep formations and wells with multiple completions, as well as to handle corrosive fluids. Optimization of these for CO_2 sequestration may require methods of optimizing sequestration efficiency. The engineering and cost-related issues of transportation and compression of CO_2 have not been considered here but will need to be added, along with other engineering issues such as effects of contaminants in the CO_2 stream, before large-scale testing occurs. Potential needs include

- methods of injecting additives for controlling the mobility of CO_2
- advanced well completion technology for enhancing sweep efficiency
- addition of chemical or biological additives for enhancing mineral trapping
- development and emplacement of in situ sensors for monitoring CO_2 migration
- injection technologies to limit CO_2 migration beyond “spill-points” and through leaks in the caprock

5.3.5 Performance Assessment

Multiphase, multicomponent computer simulators of subsurface fluid flow have been developed for oil and gas reservoirs, natural gas storage, groundwater resource management, and groundwater remediation. The accuracy of these simulators depends heavily on site- and project-specific calibration and improves by continual parameter adjustment over the project lifetime. Developing reliable tools for predicting, assessing, and optimizing CO_2 sequestration will require a similar level of experience under actual operating conditions. Additional needs specific to CO_2 sequestration include

- reactive chemical transport codes with precipitation-dissolution and adsorption-desorption kinetics and
- coupled H-C-M (hydrological-chemical-mechanical) models for long-term behavior and assessment of induced micro-seismicity.

5.3.6 Monitoring

Monitoring of CO_2 migration in the subsurface is needed for large-scale sequestration of CO_2. Tracking of the distribution of trapped CO_2 in the gaseous, dissolved, and solid phases is needed for performance confirmation, leak detection, and regulatory oversight. Existing monitoring methods include well testing and pressure monitoring; tracers and chemical sampling; and surface and borehole seismic, electromagnetic, and geomechanical methods such as tiltmeters. The spatial and temporal resolution of these methods is unlikely to be sufficient for performance confirmation and leak detection. Needs include

- high-resolution mapping techniques for tracking migration of sequestered CO_2 and its byproducts
- deformation and microseismicity monitoring
- remote sensing for CO_2 leaks and land surface deformation

5.3.7 Cross-Cutting Fundamental Research Needs

As the individual road maps for these geologic formations were developed, several cross-cutting fundamental research needs emerged. New and improved understanding of these issues will lead to safer and more cost-effective CO_2 sequestration. An expanded discussion of fundamental research needs can be found in Dove et al.

Multiphase transport in heterogeneous and deformable media: Gravity segregation, viscous fingering, and preferential flow along high-permeability pathways will play a dominant role in CO_2 migration in the subsurface. These difficulties will be compounded by deformation accompanying adsorption-desorption processes and precipitation-dissolution processes. A better fundamental understanding is needed to predict migration of CO_2 and to optimize sweep efficiency in geologic formations.

Phase behavior of CO_2/petroleum/water/solid systems: The partitioning of CO_2 between the brine, oil, gas, and solid phases is critical to understanding trapping mechanisms, as well as to predicting CO_2-enhanced oil recovery from petroleum formations and enhanced gas recovery from coal formations. Better understanding of the solid/fluid partitioning, particularly, is needed for optimizing enhanced gas recovery from coal-bed methane projects.

CO_2 dissolution and reaction kinetics: Although the principal reaction pathways between CO_2 and sedimentary formations are relatively well understood (e.g., reactions of feldspars with acid to form calcite, dolomite, siderite and clay; dissolution of carbonate minerals), the kinetics of CO_2 dissolution in the liquid phase and subsequent rock-water reactions are slow and poorly understood. If conversion of CO_2 to these stable mineral phases is to be an important component of sequestration in brine formations, understanding of the kinetics of these reactions and the processes controlling them is essential.

Coupled H-M-C-T (hydrologic-mechanical-chemical-thermal) processes and modeling: Accurately predicting, assessing, optimizing, and confirming the performance of a sequestration project requires an accurate coupled model of all of the processes that influence repository performance and safety. While much experience in subsurface simulation has been gained from the oil and gas industry and from the groundwater management and remediation industries, other experience shows that the quality of our predictions depends strongly on having a simulator geared toward the specific application. Simulators tailored to the specific physical and chemical processes important for CO_2 sequestration must be developed, tested, calibrated, and refined through operational experience.

Micromechanics and deformation modeling: Production of oil and gas from geologic formations and subsequent sequestration of CO_2 into geologic formations will be accompanied by deformation of the reservoir formation. The influence of deformation on the hydraulic properties of the formation and integrity of the caprock must be better understood. In brine formations, unlike in oil and gas reservoirs where injection of CO_2 is accompanied by withdrawal of fluids, deformation is likely to be widespread as the pressure builds in the formation. The effects of deformation on the integrity of the caprock and its ability to induce seismic events must be better understood to ensure the long-term stability and safety of CO_2 sequestration.

High-resolution geophysical imaging: High-resolution geophysical imaging offers the best potential for cost-effective monitoring of the migration and byproduct formation of CO_2 in subsurface environments. Three-dimensional and four-dimensional (time-lapse) images of geologic structures and pore fluids can be created with surface, surface-to-borehole, and cross-borehole techniques. The resolution needs to be improved if these methods are to be relied on to detect caprock leakage, formation of viscous fingers, and preferential pathways.

5.4 ADVANCED CONCEPTS FOR SEQUESTRATION IN GEOLOGIC FORMATIONS

The sequestration techniques described draw heavily from current approaches used by industry for production of oil, gas, and coal-bed methane and for storage of natural gas. Although these techniques provide reasonable near-term options for sequestration of CO_2, enhanced technology for CO_2 sequestration in geologic formations may significantly decrease costs, increase capacity, enhance safety, or increase the beneficial uses of CO_2 injection. Such enhanced technologies include the following:

- **Enhanced mineral trapping with catalysts or other chemical additives.** Conversion of CO_2 to stable carbonate minerals is expected to be very slow under the current scenarios envisioned for sequestration in geologic formations. Identification of chemical or biological additives that increase reaction rates could enhance the effectiveness of mineral trapping.

- **Sequestration in composite formations.** Multilayer formations, all with imperfect caprocks, may result in highly dispersed plumes of CO_2. The greater the degree of dispersion, the greater the opportunity for efficient solubility and mineral trapping. Developing design criteria that account for acceptable leakage across multilayer formations could increase the geographic distribution and capacity of geologic formations for sequestering CO_2.

- **Microbial conversion of CO_2 to methane.** Microorganisms that generate methane from CO_2 (methanogens) are known to exist in a wide variety of oxygen-depleted natural environments. If sequestration sites could be chosen to take advantage of this naturally occurring process, an underground “methane factory” could be created. Alternatively, additives that stimulate methanogenesis could be injected along with CO_2 to promote methane formation.

- **Rejuvenation of depleted oil reservoirs.** Injection of CO_2 into active oil reservoirs is a widely practiced EOR technique. However, even after the EOR process is no longer economically feasible, as much as 50% of the original oil in place may be left underground. CO_2

injection, followed by a quiescent period during which gravity drainage and gas cap formation redistribute the gas and liquid phases, may rejuvenate an oil formation that can no longer produce economically. The injected CO_2 is sequestered in the geological formation.

- **CO_2-enhanced production of methane hydrates:** Methane hydrates in ocean sediments and permafrost hold tremendous reserves of natural gas. Producing gas from these formations remains a challenge because of their complex structure, mechanical properties, and the thermodynamic behavior of hydrates. CO_2 injection into methane hydrate formations may enhance production while simultaneously sequestering CO_2.

5.5 OVERALL R&D PRIORITIES

Geologic sequestration is unique among the options for sequestration of CO_2 because of the extensive experience from related industries: oil and gas production, groundwater resource management, and groundwater remediation. Nevertheless, a number of critical needs must be addressed to make geologic formation a cost-competitive and safe option for sequestration of CO_2. These have been addressed in detail in the previous sections of the report. Figure 5.6 provides synthesis and a timeline for a key set of actions needed to accelerate development of a set of options for CO_2 sequestration in geologic formations. Short-term needs feed into longer term projects. Together these will provide a realistic assessment and cost and performance data for large-scale sequestration of CO_2 in geologic formations. The paragraphs below elaborate on these key actions.

1. Fundamental research is needed to aid understanding of critical processes and parameters that will contribute to safe and effective CO_2 sequestration.

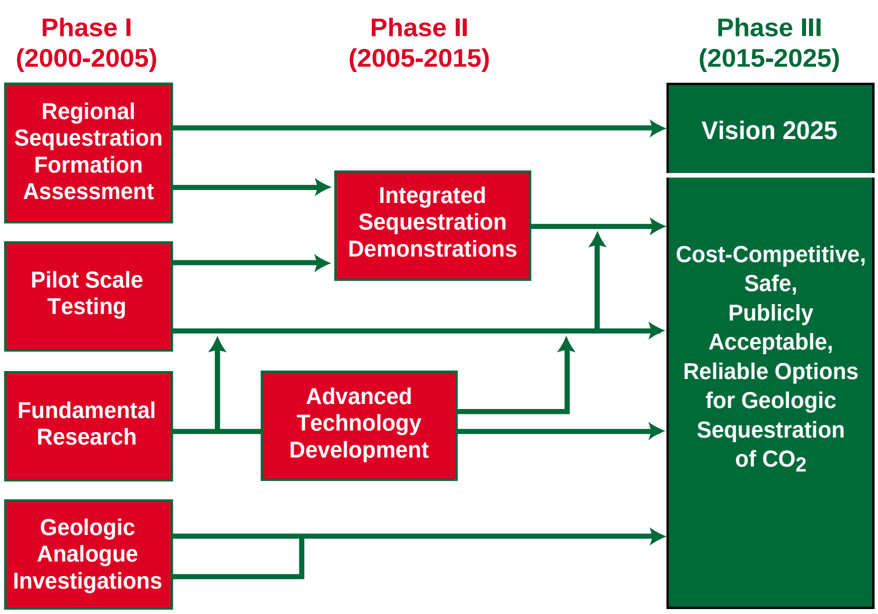


Fig. 5.6. Key elements of the R&D road map for sequestration of CO_2 in geologic formations.

2. There must be a reliable assessment of geologic formations available for sequestration of CO_2 from each of the major power-generating regions of the United States. Screening criteria for choosing suitable options must be developed in partnership with industry, the scientific community, the public, and regulatory oversight agencies.
3. Pilot tests of geologic sequestration conducted early would help develop cost and performance data and help prioritize future R&D needs. These pilot tests should be designed and conducted with sufficient monitoring, modeling, and performance assessment to enable quantitative evaluation of the processes responsible for geologic sequestration.
4. Geologic analogues, such as CO_2 reservoirs and CO_2-rich aquifers, should be studied to determine the factors leading to caprock integrity and mineral-trapping mechanisms.
5. Advanced technologies are needed for (1) increasing the volume of the geologic formation filled by CO_2, (2) creating stable long-term sinks (stable mineral assemblages), (3) increasing solubility and perhaps diluting CO_2 to acceptable levels, and (4) tracking migration of CO_2 in the subsurface.
6. Full-scale demonstration projects, performed in partnership with industry, that integrate CO_2 separation and transportation with geologic sequestration are needed to provide cost, safety, and performance data on geologic sequestration of CO_2.

The road map effort discussed here included a number of working group meetings and extensive external review of the draft by stakeholders. The consensus of these groups was that all of the potential formations for gelologic sequestration should be investigated simultaneously. The stakeholder groups also pointed out that the geologic formations about which we know the most, namely oil and gas reservoirs, are probably the first candidates for pilot testing and implementation of sequestration. The highest priority for fundamental research to expand our current understanding, however, should be the reservoirs about which we know the least, namely brine and coal-bed formations. In addition, cross-cutting research on methods to predict and monitor the performance and safety of CO_2 injection will be essential components of the research effort.

It was also recommended that the R&D program be organized to take advantage of the common aspects of sequestration among all formation types. This approach would maximize synergy and minimize overlap. For example, all of the formations contain brine; these should be studied as a system rather than as particular types of formations. Similarly, monitoring methods before, during, and after injection are likely to be similar for each formation type and should be jointly developed and tested. Finally, engineering studies that provide technology assessment, cost/benefit analyses, and technology enhancements can be shared.

5.6 WORKS CONSULTED

Ayers, W. B., and B. S. Kelso 1989. “Knowledge of Methane Potential for Coalbed Resources Grows, but Needs More Study,” *Oil & Gas Journal,* (October 23): 64–7.

Bachu S., W. D. Gunter, and E. H. Perkins 1994. “Aquifer Disposal of CO_2:

Hydrodynamic and Mineral Trapping," *Energy Convers. Mgmt.* 35: 269–79.

Baes, C. F., Jr., S. E. Beall, and D. W. Lee 1980. "The Collection, Disposal and Storage of Carbon Dioxide" pp. 495–519 in *Interactions of Energy and Climate*, W. Bach, J. Pankrath, and J. Williams, eds., D. Reidel Publishing.

Battistelli, A., C. Calore, and K. Pruess 1997. "The Simulator TOUGH2/EWASG for Modeling Geothermal Reservoirs with Brines and Non-Condensible Gas," *Geothermics*, 26 (4): 437–64.

Bayles, G. A., and A. A. Reznik 1986. *An Evaluation of the Effect of Methane Adsorption/Desorption in Well Tests on Coalbeds,* Chemical and Petroleum Engineering Department, University of Pittsburgh, Pittsburgh, Pa. (Work performed for DOE under contract DE-AH-85MC03193.)

Beckman, K. L., and P. L. Determeyer 1995. *Natural Gas Storage: Historical Developments and Expected Evolution,* GRI-95/0214, available at www.gri.org/toplevel.html.

Bell, G. J., and K. C. Rakop 1986. "Hysteresis of Methane/Coal Sorption Isotherms," SPE 15454, in *Proceedings of the 61st Annual Technical Conference and Exhibition of the Society of Petroleum Engineers,* New Orleans, La., October 5–8, 1986.

Bergman P. D., and E. M. Winter 1995. "Disposal of Carbon Dioxide in Aquifers in the U.S.," *Energy Convers. Mgmt.* 36: 523–6.

Bergman P. D., E. M. Winter, and Z. Y. Chen 1997. "Disposal of CO_2 in Depleted Oil and Gas Reservoirs," *Energy Convers. Mgmt.* 38: suppl. pp. S211–S216.

Briggs, H., and R. P. Sinha 1933. "Expansion and Contraction of Coal Caused Respectively by the Sorption and Discharge of Gas," *Proceedings Roy. Soc. of Edinburgh*, 53: 48–53.

Bumb, A. C., and C. R. McKee 1988. "Gas-well Testing in the Presence of Desorption for Coalbed Methane and Devonian Shale," *SPE Formation Evaluation,* 3(1): 179–85.

Burruss, R. C. 1977. *Analysis of Phase Equilibria in C-O-H-S Fluid Inclusions,* Mineral. Assoc. Of Canada Short Course Handbook 6, pp. 39–74.

Butt, D. P., K. S. Lackner, C. H. Wendt, S. D. Conzone, H. Kung, Y. C. Lu, and J. K. Bremser 1996. "Kinetics of Thermal Dehydroxylation and Carbonation of Magnesium Hydroxide," *J. Am. Ceram. Soc.* , 79: 1892–8.

Byrer, C. W., and H. D. Guthrie 1997. "Assessment of World Coal Resources for Carbon Dioxide (CO_2) Storage Potential— While Enhancing Potential for Coalbed Methane," pp. 573–76 in *Greenhouse Gas Mitigation, Technologies for Activities Implemented Jointly, Proceedings of Technologies for Activities Implemented Jointly*, held in Vancouver, Canada, May 26–29, P. W. F. Reimer, A. Y. Smith, and K. V. Thambimuthu, eds., Elsevier, Amsterdam, The Netherlands.

Byrer, C. W., and H.D. Guthrie 1998. "Carbon Dioxide Potential in Coalbeds: A Near-term Consideration for the Fossil Energy Industry," pp. 593–600 in *The Proceedings of the 23rd International Technical Conference on Coal Utilization and Fuel Systems,* Clearwater, Fla., March 9–13, 1998, U.S. Department of Energy, Washington, D.C.

Byrer, C. W., and H.D. Guthrie 1998. "Coal Deposits: Potential Resource for Sequestering Carbon Dioxide Emissions From Power Plants," presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland, August 30–September 2, 1998. Proceedings forthcoming.

Byrer, C. W., T. H. Mroz, and G. L. Covatch 1984. "Production Potential for Coalbed Methane in U.S. Basins," SPE 12832, presented at the SPE/DOE/GRI Unconventional Gas Recovery Symposium, Pittsburgh, Pa., May 13–15, 1984.

DOE (Department of Energy) 1993. *A Research Needs Assessment for The Capture, Utilization and Disposal of Carbon Dioxide from Fossil Fuel Fired Power Plants*, DOE/ER-30194, Washington, D.C.

Dove, P., J. Harris, J. M. Logan, L. Pyrak-Nolte, F. M. Orr, Jr., P. J. Ortoleva, F. Richter, J. W. Rudnicki, N. R. Warpinski, W. R. Wawersik, J. L. Wilson, and T. F. Wong. "Terrestrial Sequestration of CO_2—An Assessment of Research Needs." Forthcoming.

Dyman, T. S., D. D. Rice, J. W. Schmoker, C. J. Wandrey, R. C. Burruss, R. A. Crovelli, G. L. Dolton, T. C. Hester, C. W. Keighin, and J. G. Palacas 1993. "Geologic Studies of Deep Natural Gas Resources in the United States," pp. 171–204 in *The Future of Energy Gases*, D. G. Howell, ed., U.S. Geological Survey, Denver, Colo.

Eddy, G. E., C. T. Rightmire, and C. W. Byrer 1982. "Relationship of Methane Content of Coal Rank and Depth: Theoretical Versus Observed," SPE / DOE Paper 10800, in *Proceedings of 1982 SPE/DOE Unconventional Gas Recovery Symposium*, Pittsburgh, Pa., May 16–18.

Fulton, P. F., B. Rogers, N. Shah, and A. A. Reznik 1980. "Study of the Effectiveness of Increasing Methane Production," Chemical and Petroleum Engineering Department, University of Pittsburgh, Pittsburgh, Pa. (Work performed for DOE under contract DE-FG-21- 79MC1083.

Fyfe, W. S., R. Leveille, W. Zang, and Y. Chen 1996. "Is CO_2 Disposal Feasible?" *Am. Chem. Soc., Div. Fuel Chem.* 41: 1433–5.

Garrels, R. M., and F. T. Mackenzie 1971. *Evolution of Sedimentary Rocks*, W. W. Norton, New York.

Gunter, W. D., E. H. Perkins, and T. J. McCann 1993. "Aquifer Disposal of CO_2-rich Gases: Reaction Design for Added Capacity," *Energy Convers. Mgmt.* 34: 941–8.

Gunter, W. D., T. Gentzis, B. W. Rottenfusser, and R. J. H. Richardson 1996. "Deep Coalbed Methane in Alberta, Canada: A Fuel Resource with the Potential of Zero Greenhouse Gas Emissions," pp. 217–22 in *Proceedings of the Third International Conference on Carbon Dioxide Removal*, Cambridge, Mass., September 9–11, 1996.

Gunter, W. D., S. Bachu, D. H. S. Law, V. Marwaha, D. L. Drysdale, D. E. MacDonald, and T. J. McCann 1996. "Technical and Economic Feasibility of CO_2 Disposal in Aquifers within the Alberta Sedimentary Basin, Canada," *Energy Convers. Mgmt.* 37: 1135–42.

Gunter W. D., B. Wiwchar, and E. H. Perkins 1997. "Aquifer Disposal of CO_2-rich Greenhouse Gases: Extension of the Time Scale of Experiment for CO_2-sequestering Reactions by

Geochemical Modeling," *Mineral. and Petrol.* 59: 121–40.

Harpalani, S., and X. Zhao 1989. "The Unusual Response of Coal Permeability to Varying Gas Pressure and Effective Stress," pp. 65–72 in *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources: Proceedings of the 30th U.S. Symposium*, A. Wahab Kahir, ed., West Virginia University, Morgantown, W.V., June 19–22, 1989.

Hendricks, C. A., and K. Blok 1995. "Underground Storage of Carbon Dioxide," *Energy Convers. Mgmt.* 36: 539–42.

Hertzog, H. J., and E. M. Drake 1998. "CO_2 Capture, Reuse, and Sequestration Technologies for Mitigating Global Climate Change," pp. 615–26 in *Proceedings of the 23rd International Technical Conference on Coal Utilization & Fuel Systems,* Clearwater, Fla., March 9–13.

Hitchon, B., ed. 1996. *Aquifer Disposal of Carbon Dioxide, Hydrodynamic and Mineral Trapping–Proof of Concept,* Geoscience Publishing Ltd., Sherwood Park, Alberta, Canada.

Holloway, S. 1996. "An Overview of the Underground Disposal of Carbon Dioxide, British Geological Survey," pp. 193–8 in *Proceedings of the Third International Conference on Carbon Dioxide Removal*, Cambridge, Mass., September 9–11, 1996.

Holloway, S. 1997. "An Overview of the Underground Disposal of Carbon Dioxide," *Energy Convers. Mgmt.* 38: s193–s198.

Holloway, S., and D. Savage 1993. "The Potential for Aquifer Disposal of Carbon Dioxide in the UK," *Energy Convers. Mgmt.* 34: 925–32.

Joubert, J. I., C. T. Grein, and D. Bienstock 1973. "Sorption of Methane in Moist Coal," *Fuel,* 52 (3): 181.

Kim, A. G. 1977. *Estimating Methane Content of Bituminous Coalbeds from Adsorption Data,* BM-RI-8245, U.S. Bureau of Mines, Pittsburgh, Pa.

Koide, H., Y. Tazaki, Y. Noguchi, S. Nakayama, M. Iijima, K. Ito, and Y. Shindo 1992. "Subterranean Containment and Long-Term Storage of Carbon Dioxide in Unused Aquifers and in Depleted Natural Gas Reservoirs," *Energy Convers. Mgmt.* 33 (5–8): 619–26.

Korbol, R., and A. Kaddour 1995. "Sleipner Vest CO_2 Disposal—Injection of Removed CO_2 into the Utsira Formation," *Energy Convers. Mgmt.* 36 (6–9): 509–12.

Lackner, K. S., C. H. Wendt, D. P. Butt, E. L. Joyce, and D. H. Sharp 1995. "Carbon Dioxide Disposal in Carbonate Minerals," *Energy*, 20: 11–70.

Law, D. H. S., and S. Bachu 1996. "Hydrogeological and Numerical Analysis of CO_2 Disposal in Deep Aquifers in the Alberta Sedimentary Basin," *Energy Convers. Mgmt.* 37 (6–8): 1167–74.

Layne, A. W., and C. W. Byrer 1988. "Analysis of Coalbed Methane Stimulations in the Warrrior Basin, Alabama," *SPE Formation Evaluation*, 3: 663–70.

Layne, A. W., H. J. Siriwardane, and C. W. Byrer 1988. "Assessment of Gas Production Potential From Coalbeds and Adjacent Strata," SPE Paper 17765, in *Proceedings of Gas Technology Symposium,* Dallas, Tex., June 1988.

Lee, Y. H. 1982. *Methane Recovery from Coalbeds: Effects of Monolayer Capacity and Pore Structure on Gas Content,* masters thesis, University of New Mexico at Albuquerque.

Lohuis, J. A. O. 1993. "Carbon Dioxide Disposal and Sustainable Development in The Netherlands," *Energy Convers. Mgmt.* 34 (9–11): 815–21.

McCulloch, C. M., J. R. Levine, F. N. Kissell, and M. Duel 1975. *Measuring the Methane Content of Bituminous Coalbed,* RI8043, U.S. Department of the Interior, Washington, D.C.

McElhiney, J. E., R. A. Koenig, and R. A. Schraufnagel 1989. "Evaluation of Coalbed-Methane Reserves Involves Different Techniques," *Oil & Gas Journal,* (October 30): 63–72

Moffat, D. H., and K. E. Weale 1955. "Sorption by Coal of Methane at High Pressures," *Fuel* 34: 449–62.

Nelson, C. R. 1989. *Chemistry of Coal Weathering,* Elsevier, New York.

Pearce, J. M., S. Holloway, H. Wacker, M. K. Nelis, C. Rochelle, and K. Bateman 1996. "Natural Occurrences of CO_2 as Analogues for the Geologic Disposal of Carbon Dioxide," *Energy Convers. Mgmt.* 37 (6–8):1123–8.

Reznik, A. A., P. K. Singh, and W. L. Foley 1982. *Enhanced Recovery of In-Situ Methane By Carbon Dioxide Injection: An Experimental Feasibilty Study*, Chemical and Petroleum Engineering Department, University of Pittsburgh, Pittsburgh, Pa. (Work Performed for DOE under contract DE-FG21-80 MC14262.)

Ruppel, T. C., C. T. Grein, and D. Bienstock 1974. "Adsorption of Methane on Dry Coal at Elevated Pressure," *Fuel* 53: 152.

Scheidegger, A. E. 1974. *The Physics of Flow through Porous Media,* 3rd Ed., University of Toronto Press, Buffalo, N.Y.

Seifritz W. 1990. "CO_2 Disposal by Means of Silicates," *Nature* 345: 486.

Stevens, S. H., J. A. Kuuskraa, and D. Spector 1998. "CO_2 Sequestration in Deep Coal Seams: Pilot Results and Worldwide Potential," presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland, August 30–September 2, 1998. Proceedings forthcoming.

Surinova, S. I., and A. N. Polushkin 1987. "The Role of the Wettability of Coal in the Production of Carbonaceous Adsorbents," *Solid Fuel Chemistry* 21 (4): 166–120.

Yalcin, E., and S. Durucan 1991. "Methane Capacities of Zonguldak Coals and the Factors Affecting Methane Adsorption," *Mining Science and Technology,* 13: 215–22.

van der Meer, L. G. H. 1992. "Investigations Regarding the Storage of Carbon Dioxide in Aquifers in The Netherlands," *Energy Convers. Mgmt.* 33 (5–8): 611–18.

Weir, G. J., S. P. White, and W. M. Kissling 1995. "Reservoir Storage and Containment of Greenhouse Gases," pp. 233–8 in K. Pruess, ed., *Proceedings of the TOUGH Workshop '95*, LBL-37200, Lawrence Berkeley National Laboratory, Berkeley, Calif.